DEVELOPMENTS TOWARD LASER DIODE DRIVEN BISTABLE PHOTOCONDUCTIVE SWITCHES (BOSS)

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ABSTRACT

The Bistable Optically controlled Semiconductor Switch (BOSS) is the only completely controllable high power solid state switch which operates on sub-nanosecond to microsecond time scales. The present state of BOSS technology is discussed, including the limits of operation and potential extensions of these limits. Experiments to measure the electric field distribution during switching and the threshold breakdown fields for small gap ($\approx$10's of μm) GaAs switches are described. From these results, operating parameters for a laser diode controlled BOSS configuration are presented.

1. INTRODUCTION

Pulsed power systems are commonly operated with closing switches which cannot be subsequently opened while current is flowing. As a result the performance characteristics (notably pulse width) of such a circuits are determined by the physical construction of the circuit (capacitance and inductance in a pulse forming network, or physical length of a line-type pulser). A switch with both closing and opening capability offers independence from the energy storage portion of the circuit and greater flexibility.

Figure 1 shows a schematic description of the geometry of the Bistable Optically controlled Semiconductor Switch (BOSS)[1]. A high resistivity semiconductor is used as the switching device in a pulsed power circuit and illuminated with light of two different photon energies, $h\nu_1$ and $h\nu_2$, at times t_1 and t_2 respectively. Figure 1 also shows the response of the circuit. At t_1 the switch is turned on by the first light source, $h\nu_1$, and current flows through the load. Ideally, the load remains activated until time t_2, when the second light source, $h\nu_2$, returns the semiconductor to a high resistance and the circuit turns off.

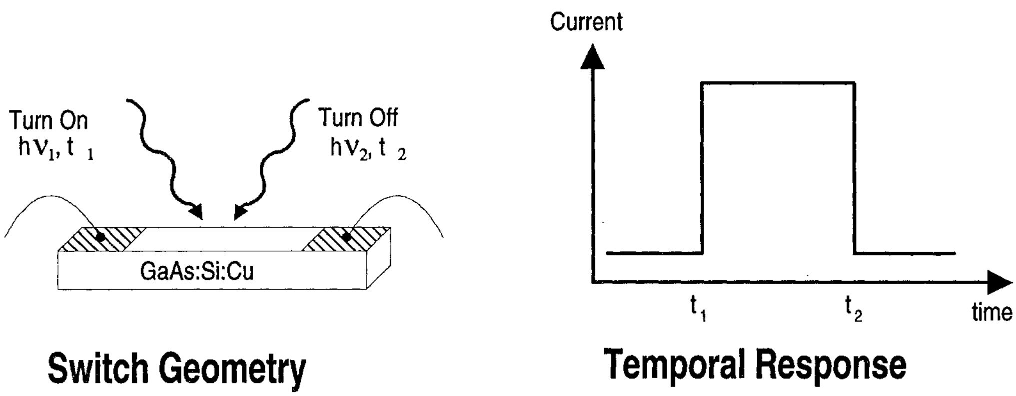

Figure 1 - Schematic switch geometry and circuit response of typical BOSS switch.

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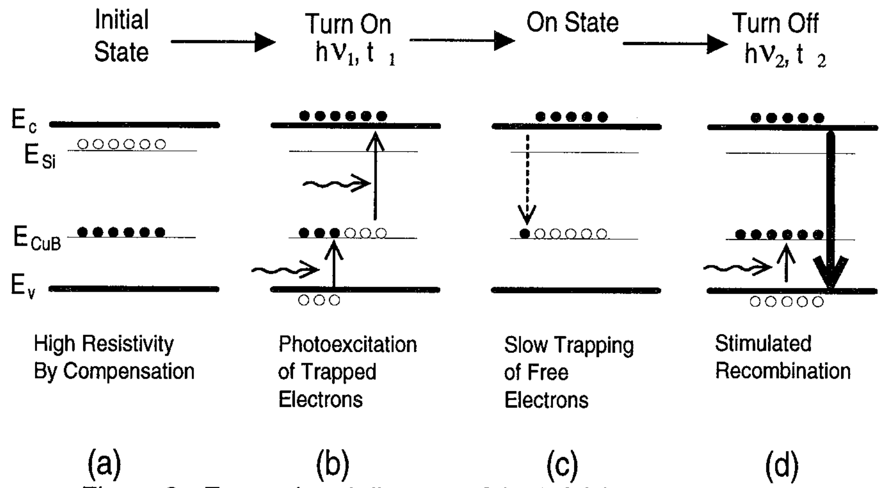


Figure 2 - Energy band diagram of the BOSS switching cycle.

Several materials have been shown to exhibit bistable characteristics, but GaAs has been the most thoroughly studied for high power circuits[2-6]. The material used in this case is silicon doped (n-type) GaAs closely compensated with Cu, an acceptor with two main levels at 0.13 and 0.44 eV above the valence band. The level at 0.44 eV (often referred to as Cu_B) has a large capture cross-section for holes, but a small one for electrons. The implications of this are shown in the schematic switching cycle of Figure 2.

In the off state (Figure 2a) the Cu levels are filled with electrons from the Si donors. Careful compensation can produce material with resistivity of about 10^6 Ω-cm[7]. Illuminating the material with light of photon energy $h\nu_1 > 1$eV is sufficient to excite electrons from Cu_B to the conduction band and holes from the valence band to the Cu_B level, and results in a large concentration of electrons in the conduction band, turning the switch on (Figure 2b). The Cu_B level quickly traps holes from the valence band. The electron density in the conductiont band, however, decays with a long time constant because the trapping cross-section of Cu_B for electrons is extremely small (10^{-21} cm^2)[4]. The material stays in a high conductivity state for much longer than the natural recombination time of GaAs, up to 50 µs compared with "natural" times of the order of ns[8]. Illuminating the material with light of lower photon energy, $h\nu_2$ (Figure 2c), excites electrons from the valence band into the Cu_B level, but cannot excite electrons from Cu_B to the conduction band. The holes in the valence band then directly recombine with the conduction band electrons and return the material to a high resistivity state (Figure 2d).

2. BOSS OPERATING PARAMETERS

BOSS technology with GaAs switches has been successfully demonstrated over a wide parameter space[5,6]. The range of operating performance currently achieved is summarized in Table I. Turn on with these switches is usually accomplished with 1.06 µm (1.16 eV photon energy) radiation from the fundamental output of Nd:YAG lasers. The energy density to turn the switch on is related to the density of Cu_B states which must

Parameter	Range
Laser Energy Density	
Turn-On (1.06 µm)	20 mJ/cm^2
Turn-Off (1.7-2 µm)	20 mJ/cm^2
On-State Conductivity	<20 (Ω-cm)$^{-1}$
Turn-On Risetime	100 ps (laser limited)
On-Time	600 ps - 10 µs
Turn-Off Fall-Time	>100 ps
Hold-Off Field after Opening	
-Without irradiation	~10 kV/cm
-Neutron irradiated	>36 kV/cm

Table I - Typical BOSS operating parameters.

be ionized. Assuming 100% absorption of the incident radiation and exact compensation of GaAs doped with $2x10^{16}$ cm^{-3} Si donors, a volume energy density of at least 3.7 mJ/cm^3 must be deposited into the switch material from the turn-on laser in order to ionize all Cu_B traps. Given that switches are often made from commercial wafer material with thickness of about 0.05 cm, the area energy density requirement would be at least 0.2 mJ/cm^2 for optimal operation. The maximum on-state conductivity for $2x10^{16}$ cm^{-3} Cu_B states is σ = 16 $(\Omega\text{-cm})^{-1}$, assuming a conduction band mobility of 5000 $cm^2/Vsec$. The reported experimental values of maximum conductivity are consistent with this value, so the switches are operating with nearly complete ionization of the Cu_B state. The laser energy density for this conductivity range, however, is about 20 mJ/cm^2, indicating that the incident energy is absorbed by the Cu_B level with 1% efficiency.

Turn-on time is in general limited only the by rate at which the required energy can be deposited into the switch volume (ignoring circuit effects). The fastest experimentally observed rise times are about 100 ps, limited primarily by the laser.[5]

The conduction or on-state time of a BOSS switch is related to the cross-section for electrons to be trapped by the Cu_B states which have captured holes. Si doped Cu compensated GaAs displays on-times ranging from 100's of ns to 10's of µs, depending on whether the material was over or under-compensated. Similar BOSS material additionally treated with neutron irradiation is limited to conduction times of 1 to 10 ns due to enhanced recombination through damage induced recombination centers[5,9].

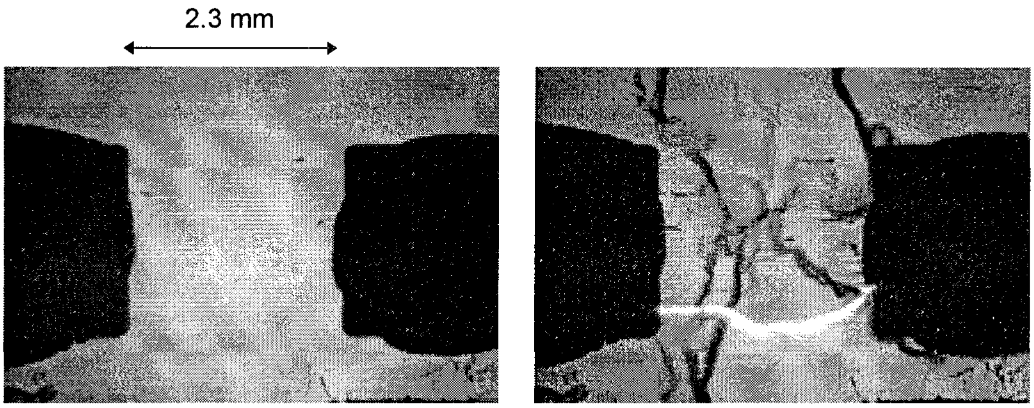
The turn-off laser photon energy must be >0.44 eV and <1 eV in order to excite electrons into the Cu_B state and allow recombination to turn the switch off. Experimentally, the turn-off wavelength has been at 1.7 µm (0.73 ev) or 2.12 µm (0.59 eV), determined by available laser equipment. Higher photon flux is required to turn off the switch, since hole retrapping is a competing process. However, the lower photon energy tends to balance this requirement such that the net energy density requirement for turn-off is approximately the same as for turn-on, ~20 mJ/cm^2.

Turn-off time is a function of both incident laser intensity (i.e. the rate at which electrons are ionized into the Cu_B level) and recombination time for the material. The turn-off laser generates the conditions under which direct recombination occurs. The speed of turn-off is limited by the slower of the two. Non-neutron irradiated material is relatively slow (1 to 10 ns, material limited) while neutron irradiated material has been turned off in about 100 ps (possibly laser limited)[5].

Both BOSS and "linear" photoconductive GaAs switches tend to breakdown into a persistent conduction mode generally termed lock-on. BOSS switches made with non-irradiated material can open against a rising field to a limit of about 10 kV/cm. Beyond that level the switch does not stay open, but instead locks-on with an average field of about 5 kV/cm.[6] Neutron irradiated samples have been able to open against fields as high as 36 kV/cm[5]. Materials with shorter carrier lifetime have generally higher lock-on fields.

3. EXPERIMENTS ON MICRO-GAP SWITCHES

The efficiency of a switch (ratio of switched energy to control laser energy) is quadratically dependent on the device length. With the goal of improved BOSS efficiency, we have therefore concentrated on reduced switch size through better understanding of breakdown in GaAs by focussing on the electric field distribution during the switching cycle. An optical method based on the Franz-Keldysh effect has previously been used to map the spatial and temporal evolution of the electric fields at the threshold of lock-on in GaAs switches of millimeter scale. This method has been reported in detail elsewhere[10-12]. Briefly, variations in the absorption of photons with energy slightly below the band-gap can be related to the local electric field in a material. Increased absorption indicates increased electric fields. Figure 3 shows an example of this method applied to a 2.3 mm semi-insulating GaAs switch (i.e. not BOSS). Figure 3a shows the image pattern for an unbiased switch, with the dark square regions indicating the contact regions. Figure 3b shows the same switch probed after switching when operated at an average field of 12 kV/cm, slightly above the threshold for lock-on. The dark patterns appearing throughout the space between the contacts correspond to regions with local fields in excess of 50 kV/cm, more than 4 times the average applied field. The regions displayed a typical size of 100 to 200 µm in many of these measurements. The white filament connecting the contacts is a breakdown current path, evidenced by recombination radiation.



(a) E = 0 (b) E = 12 kV/cm

Figure 3 - Absorption images of electric fields in semi-insulatig GaAs during switching.

Assuming lock-on initiates in these high-field domains, we propose that a device with gap spacing of the order of a domain width or less might be able to withstand average applied fields of about 50 kV/cm without transiting into lock-on. Recent measurements suggests support for this hypothesis. Figure 4 shows the experimental arrangement. Light from a laser diode operating at 902 nm was focused through the gap of a micro-switch to be tested. Transmitted light was collected with a microscope and detected with a computer controlled CCD camera. Resolution of < 5 µm was possible with this arrangement.

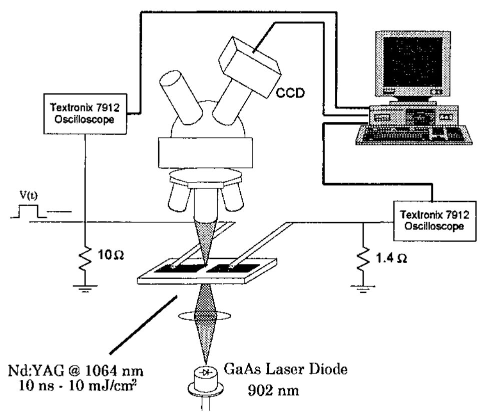


Figure 4 - Experimental setup for micro-switch absorption imaging

Switches were fabricated on double polished semi-insulating GaAs wafers 650 µm thick using standard photolithography techniques. Contact metallization consisted of thermally evaporated Au:Ge about 100 nm thick. Problems with lift-off of the photoresist after metallization resulted in some edge roughness of about 5 µm extent. Switches with gap spacing between 10 and 200 µm were produced for these tests.

Electrical contact and mechanical support of the switches was provided by a micro-probe station. A Gallium-Indium eutectic alloy which is liquid at room temperature was used to promote low contact resistance without risking breakage of the devices. Switches could be immersed in fluorinert to prevent surface breakdown. Voltage was applied to the switches using a lab-constructed 1 kV MOSFET pulser which was capable of driving a 10 ohm load line. The low value of impedance was chosen so that light from the laser diode probe did not itself cause switching of the devices, but resulted in somewhat slow risetime from the pulser, typically about 100 ns.

The switches were activated from the front with a Quanta Ray DCR-11 ND:YAG laser (1064 nm, 10 ns pulse width) coupled through an optical fiber. Neutral density filters were used to reduce the laser energy density to about 10 mJ/cm^2.

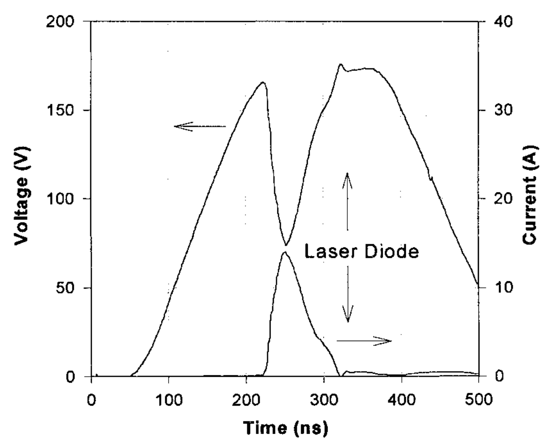


Figure 5 - Applied voltage and switched current

Figure 5 shows the voltage across and current through a 40 μm switch. The Nd:YAG laser switched the device just after the applied voltage reached 160 V (40 kV/cm average field). Current through the 1 ohm load peaked at 15 A. As the current dropped due to recombination, the switch was able to hold-off the original applied field for about 100 ns without breakdown. Also shown on the graph is the time at which the switch was probed with the laser diode.

Figure 6 shows absorption images obtained for the 40 μm switch. Figure 6a shows the raw image, while Figure 6b shows the same image processed to indicate only differences compared with a reference image in which switching did not occur. Increased absorption is evident in Figure 6b, extending 10 - 20 μm from the cathode contact and bounding it uniformly. Neglecting heating effects, this region indicates a uniform boundary electric field after hold-off is reestablished. Comparison with Figure 3b shows that for similar experimental conditions, the smaller gap did not exhibit the non-uniform domain structure which we believe contributes to lock-on development in the larger switches. This may explain why our micro-gap switches exhibit increased resistance to lock-on. Previous measurements showed increasing hold-off fields as the gap length decreased, with gaps as short as 10 μm exhibiting breakdown fields of nearly 70 kV/cm[10].

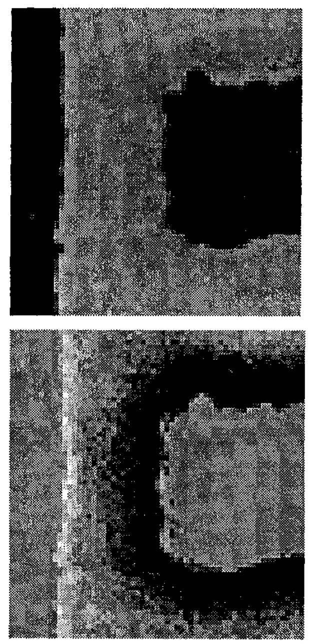


Figure 6 - Absorption image and difference image for 40 μm switch.

4. LASER DIODE TRIGGERED BOSS

Although these results are for semi-insulating GaAs switches, the threshold length dependence indicates that construction of a medium power BOSS switching device might be possible and could lead to a novel, efficient, inexpensive, laser diode-controlled switch. The small size of each switching gap, e.g. about 200 μm, matches well with the beam characteristics of semiconductor laser diodes. A proposed configuration of such a closing - opening switch is shown in Figure 7. A turn-on laser at 900 nm illuminates the switch from one side, with the thickness of the switch comparable to the absorption depth. Another laser at 1510 nm for turn-off illuminates from the other side, since the long wavelength penetration depth is approximately the same.

Taking the proposed dimensions of the device in Figure 7 (200x100x1000 μm), and using diodes which provide an optical energy of 5 mJ/cm^2, the total required optical laser energy would be 1 μJ. For a 10 ns switch rise time (equivalent to the pulse width of the laser) , this corresponds to 100 W peak optical power, a very reasonable level for present laser diode technology.

From results as shown in Fig. 5, the hold off voltage of such a device could be about 1 kV. The on state resistance for σ=20 (Ω-cm)$^{-1}$ would be about 1 Ω. The efficiency ratio (switched energy to load/trigger

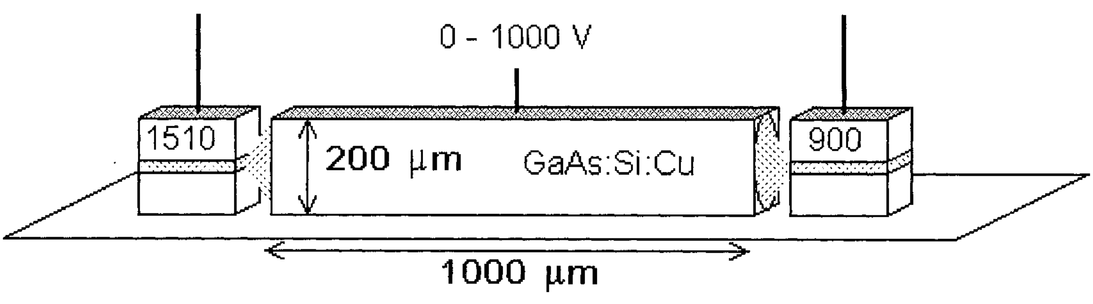


Figure 7 - Schematic integrated BOSS device configuration.

energy), η, can be written

$$\eta = \frac{V^2 \tau \ R_L \gamma}{(R_L + R_S)^2 E_{opt}} \tag{1}$$

where V is the hold-off voltage, R_L and R_S are the load and switch resistances respectively, E_{opt} is the optical energy required for switching, τ is the pulse width, and γ is the electrical efficiency of the laser diodes. Taking V = 1000, R_L = 50 Ω, γ = 0.1, τ = 500 ns, and the other parameters as noted above we find η = 1000 for this device.

A switch such as described here could be fabricated either monolithically or as a hybrid device. Unlike silicon-based optically controlled switches, the GaAs:Si:Cu switch is inherently compatible with the base material of the laser diodes that would activate it.

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